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Nonlinear Dynamic Analysis of Surface Mount Interconnects: Part II—Applications

Using the unified constitutive model and the finite element procedure presented in Part I (the preceding paper), a material nonlinear time domain dynamic analysis of a solder joint was studied for low cycle and high cycle fatigue. Thermal effects were not included in order to understand the dynamic behavior of a Pb40/Sn60 solder joint without noise-effects from thermal behavior. The latter decision was a result of observations reported in Steinberg (1988), that having in-phase or out-of-phase thermal loading in conjunction with vibrations makes a significant difference in the fatigue life. The study of fatigue under concurrent loading will be the subject of another paper.

Introduction

In many applications semiconductor devices must be able to operate in severe vibration and shock environments, such as the underhood of a vehicle. An examination of the documentation available from some component manufacturers and from publications such as MIL-STD-883 (MIL-HDBK-304, 1964) show that components are typically rated for 20 g peak sinusoidal vibrations, 1500 g of shock using a 0.005 s (200 Hz) half-sine shock pulse, and 30,000 g of acceleration for small semiconductor devices. Acceleration levels of 100 g or more are quite common in military electronic systems (Steinberg, 1988).

The frequency of the thermal cycles for semiconductor devices ranges from five cycles per minute in telecommunications equipment to one cycle per day in personal computer processors (Barker et al., 1990). The frequency range for harmonic vibrations for most vehicle and equipment is 1 to 5000 Hz (Suhir and Lee, 1988). The number of vibration cycles in a one day thermal cycle can be as high as a half-billion cycles. Therefore, damage in the solder joint due to vibrations accumulates very fast.

There is very limited work reported in the literature on material nonlinear dynamic behavior of solder joints (Barker et al., 1990). The standard practice in the electronics industry today is to use common electronic components in severe vibration and shock environments that often far exceed the ratings of these components, as it is too expensive to run high-acceleration level tests on so many different components (Steinberg, 1988).

The constitutive model and the finite element procedure proposed in Part I, Basaran and Chandaroy (1998), can be used to mitigate the need to run these expensive high-acceleration tests. Computer simulation of the dynamic behavior of the solder joints in surface mount packaging could be used to understand the behavior at acceleration levels that are too difficult or too expensive to obtain in the laboratory. A numerical analysis procedure can also be used to perform a parametric study on a new package interconnect without having to build a prototype for every possible configuration.

As a result of this research, it is shown that the contribution of vibration damage to the fatigue life of solder joints cannot be ignored in either high cycle and low cycle fatigue regions.

Parametric Study

The finite element procedure with the constitutive models presented in the preceding paper, Basaran and Chandaroy (1998), was used for dynamic analysis of a Pb40/Sn60 solder joint between a leadless ceramic chip carrier (LCCC) and a printed wiring board (PWB), depicted in Fig. 1. Because of the symmetry, only half of the system is shown. Material properties for Pb40/Sn60 are given in Basaran and Chandaroy (1998) (Part I of this paper), and, hence, are not repeated again.

In this study the ceramic chip carrier and the PWB were modeled as linear elastic, and the solder joint was modeled as viscoplastic. The material properties for the chip carrier and PWB are as follows: $E_{\text{ceramic}} = 254.9$ GPa, $\nu_{\text{ceramic}} = 0.3$, $E_{\text{PWB}} = 12.26$ GPa, and $\nu_{\text{PWB}} = 0.36$ (Basaran and Desai, 1995). The analysis was conducted at room temperature; hence, all material constants given above are for 300°K.

The package was subjected to a simultaneous two-dimensional base excitation in x and y-directions with the time history shown in Fig. 2. The parametric study included a range of acceleration values from 20 g to 4000 g, and frequencies from 10 Hz to 10,000 Hz. For some of the input motions the frequency was high enough to be considered as a shock rather than as a steady-state motion. In this study, the stress-strain and damage response of the solder joint were calculated for each cycle of dynamic loading and by using Miner's (1945) rule the cumulative damage was computed. Some of the results are presented in the following section. In the study, both low cycle and high cycle fatigue were considered. This was essential since under dynamic loading the behavior of the solder alloy can be elastic or inelastic depending on the acceleration and frequency values. For low cycle fatigue (up to 10^4 cycles, Barker et al. (1990)), the damage was calculated using the following function:

$$D = (1 - e^{-A\xi_D^Z}), \tag{1}$$

where definition of parameters is given in Basaran and Chandaroy (1998). For high cycle fatigue (over 10^4 cycles, Barker et al. (1990)), damage was calculated using the following criterion (Barker et al., 1990):

$$D = \sum \frac{n_i}{N_i}, \tag{2}$$

where n_i is the cycles experienced, and N_i is the cycles to failure at a specific elastic strain level.

For high cycle fatigue life, test data reported by Steinberg (1988) was used to obtain N_i values. The author presents high cycle fatigue plots for various solders used in electronic equipment. The plots predict the fatigue life ("number of cycles to failure") of the solder (Pb37/Sn63) due to shear stress. The

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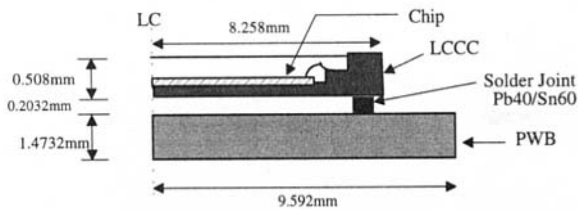


Fig. 1 Schematic section of the surface mount technology package

solder joint remains in the elastic region during a high cycle fatigue; hence, shear stress can be converted to shear strain using the shear modulus. Steinberg's (1988) test data for high cycle fatigue was converted to strain versus cycles to failure by Barker et al. (1990). In this study, the data published by Barker et al. (1990) in terms of strain versus number of cycles to failure was used. Barker et al. (1990) used shear modulus $G = 1.91 \times 10^5$ psi from Solomon's (1986) data to convert the shear stress to shear strain.

Dynamic load cycles were normalized with respect to temperature cycles (1400 s) even though there is no thermal loading applied in this study. The reason for this approach is that the fatigue life of solder joints is always defined in terms of the temperature cycles rather than the dynamic load cycles. In this study, acceleration values were normalized with respect to gravity.

The parametric study results indicate that the behavior of the solder joint is elastic for acceleration values up to 100 g, at which point it is vibrated from 10 Hz to 10,000 Hz, Figs. 3(*a*–*c*). Starting from 150 g and going to higher accelerations, inelastic behavior is observed. The behavior of the solder alloy is inelastic starting from 10 Hz to about 750 Hz (Fig. 4(*a*)). The solder joint remains in the elastic range for higher frequencies (Figs. 4(*b*) and (*c*)). This observation is consistent with the results reported by Steinberg (1988): "Solder joints that are exposed to low-rate alternating stresses will fail more quickly than solder joints that are exposed to high-rate alternating stresses." This is probably due to the fact that at lower frequencies the period of the load is higher. The time dependent viscous effects are directly related to the duration of the load application. For a longer load period, the viscous effects are bigger since the material has a longer duration to creep. As a result, the time dependent viscous effects have enough time to dominate the stress-strain behavior of the solder joint. From these observations it can be deduced that the frequency of dynamic loading can have a significant effect on the fatigue life of Pb/Sn solder alloys.

It is also observed that when the solder alloy is in the elastic range for 150 g and when frequencies starting from 750 Hz and up occur the stress level experienced by the material increases as the frequency is increased. The ultimate shear stress level at 10,000 Hz is nearly twice the shear stress at 1000 Hz (Figs. 4(*b*) and (*c*)). Yet, when the solder is experiencing viscoplastic strain, the ultimate shear stress level is approximately the same

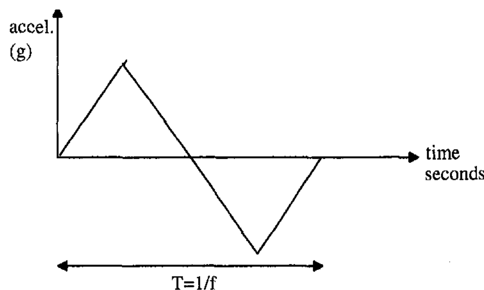


Fig. 2 The time history of the harmonic vibration input

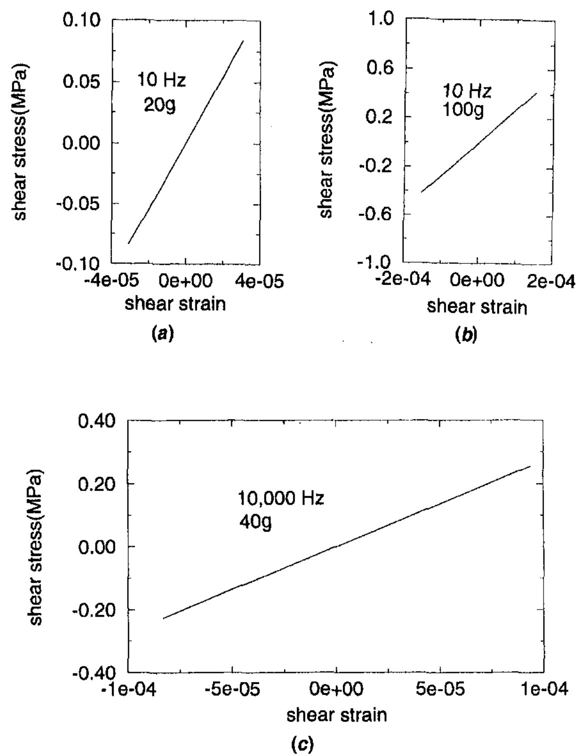
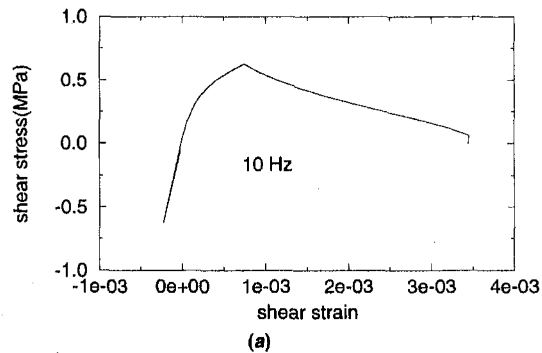


Fig. 3 Shear stress versus shear strain response of solder joint upto 100 g

for 10 Hz and 500 Hz. The strain is furthermore larger by order of magnitude for 10 Hz than 10,000 Hz.

At 300 g the behavior of the solder joint is inelastic up to 2000 Hz (Figs. 5(*a*) and (*b*)). The response is purely elastic for higher frequencies (Fig. 5(*c*)). The reason the behavior is



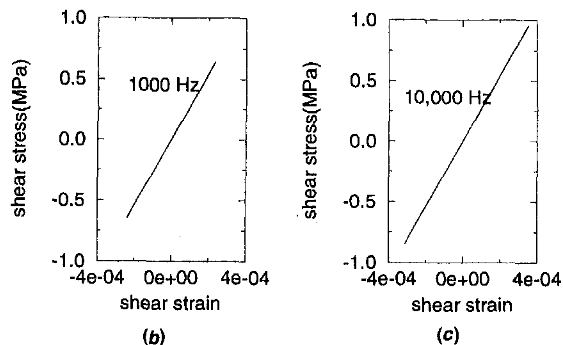


Fig. 4 Shear stress versus shear strain response of solder joint at 150 g

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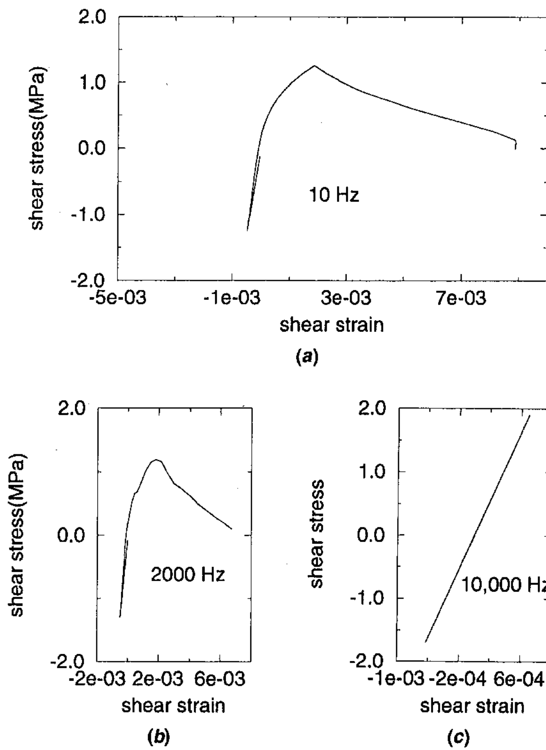

Fig. 5 Shear stress versus shear strain response of solder alloy at 300 g

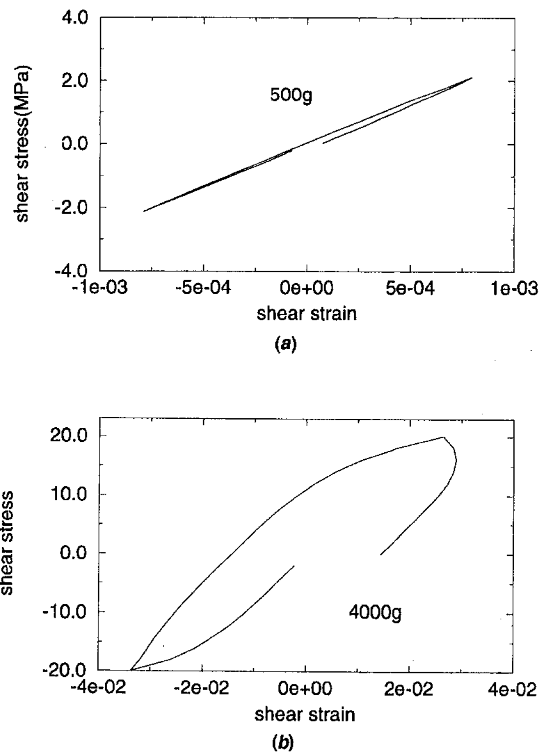

Fig. 6 Shear stress versus shear strain response of solder joint for 500 Hz

inelastic for 2000 Hz and 300 g but it is elastic for 2000 Hz and 150 g could be attributed to the fact that 300 g acceleration induces larger inertia forces than 150 g. From this result it can be deduced that the inelastic behavior of a solder alloy can be the result of the frequency value and/or acceleration intensity. Again for the same acceleration value (300 g), the shear stress level at 10,000 Hz is almost twice the shear stress at 10 Hz, but the strain level at 10 Hz is larger than that at 10,000 Hz by order of magnitude.

When the results are analyzed for the same frequency value but for varying acceleration levels, it is observed that at 500 Hz the response is inelastic for acceleration values starting from 150 g, and higher. Figures 6(*a*) and 6(*b*) show the shear stress versus shear strain response of the Pb40/Sn60 solder joint for one cycle of dynamic loading. The inelastic strain levels and ultimate stress values increase nonlinearly between different acceleration values. For relatively large acceleration values to assume that all vibration induced strains are elastic is not accurate due to the large shear strain values.

It was observed that for 100 g and lower accelerations, the large number of cycles required for failure is due to the solder joint being in the elastic range. But, it should be pointed out that when the dynamic load is concurrent with the thermal cycling, the number of cycles to failure is reduced significantly. When the temperature is increased, the viscous effects become stronger and the number of cycles to failure is reduced significantly. Steinberg (1988) reports that, "Solders are much stronger at low temperatures than at high temperatures. Higher thermal-stress levels will lead to more rapid creep-induced failures."

Figure 7 shows the damage progress versus the number of thermal cycles for 300 g and 10 Hz, 500 Hz, and 1500 Hz. The figure indicates that the damage progress is faster for lower frequency vibrations. The number of cycles to failure is relatively low, which indicates that the solder joint is experiencing low cycle fatigue. The fatigue life in this case would be significantly reduced if the ambient temperature were increased (without including the thermal cycling fatigue effects) during this dynamic loading. If the dynamic loading were to be combined with the thermal cycling, the overall fatigue life of the solder joint would be shortened substantially. This curve is a good representation of a significant effect of the damage caused in the solder joint due to dynamic loads. The results suggest that vibrational fatigue damage cannot be ignored or classified as high cycle fatigue only.

The results presented in Fig. 8 indicate that for the same frequency (such as 500 Hz) the larger acceleration causes faster damage accumulation in the material. From the figure it can be

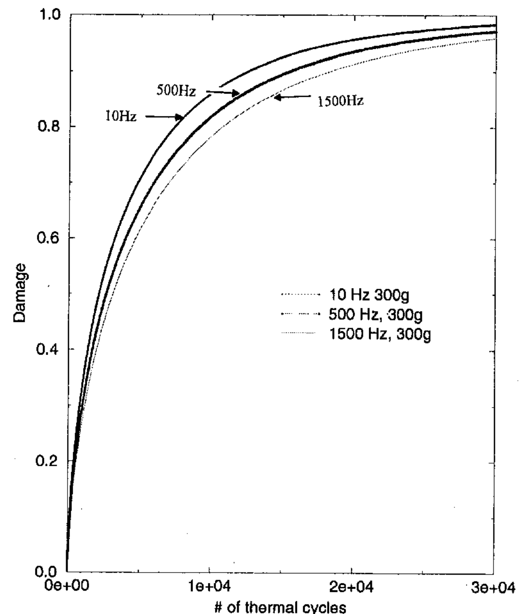

Fig. 7 Damage versus number of thermal cycles in the solder joint for 300 g

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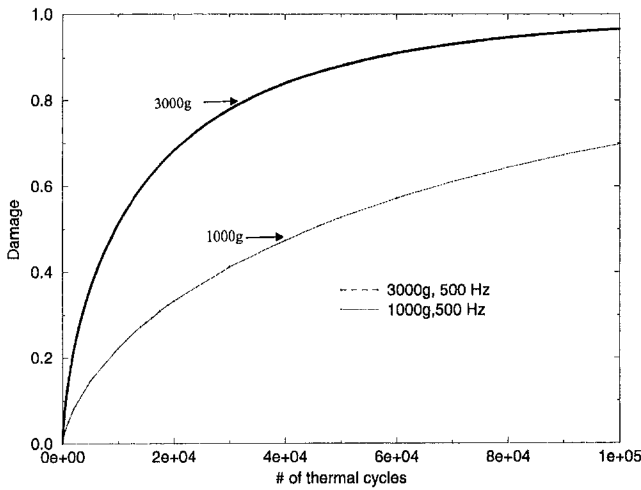


Fig. 8 Damage versus number of thermal cycles for 500 Hz

deduced that 50 percent damage accumulation occurs in 10,000 cycles for 300 g loading. On the other hand, when the acceleration level is reduced by one third, the 50 percent damage accumulation takes five times more thermal cycles to accumulate. This result indicates that the fatigue behavior of P40/Sn60 is highly nonlinear and the damage accumulation and the acceleration level are not linearly dependent.

Figure 9 depicts the accumulated energy density versus the thermal cycles. Energy density is defined as the area inside the hysteresis stress-strain hysteresis curve at each cycle. A comparison is presented for the same acceleration value and different loading frequencies. Energy dissipation in a nonconservative system is a mechanism by which the external energy is converted into internal energy as plastic work and heat. Plastic work leads to microstructural reorganization and microcraking (damage) of the material. Therefore, damage and accumulated energy density are proportional. It is observed that damage accumulation is faster in the lower frequencies. When the behavior of energy density is studied for the same frequency versus different acceleration values, the results indicate that the drop in energy density is much faster for the higher acceleration value. As a result larger acceleration values lead to a shorter fatigue life.

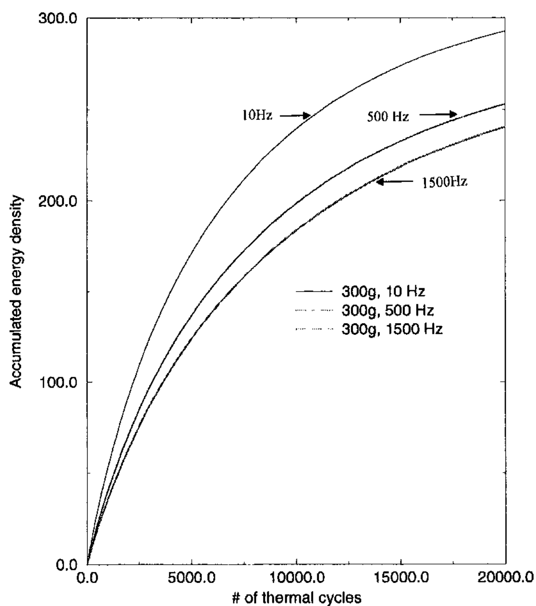
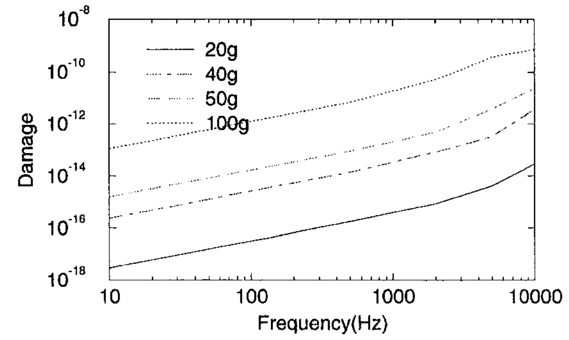


Fig. 9 Accumulated energy density versus number of thermal cycles for 300 g



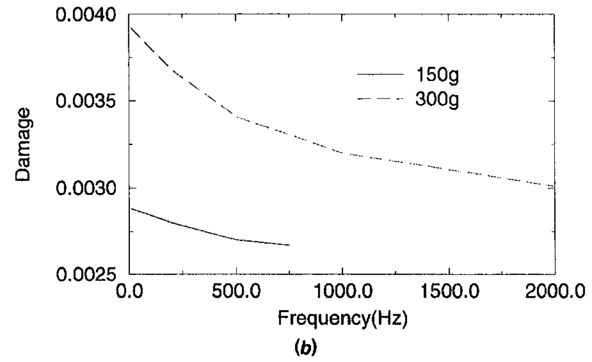
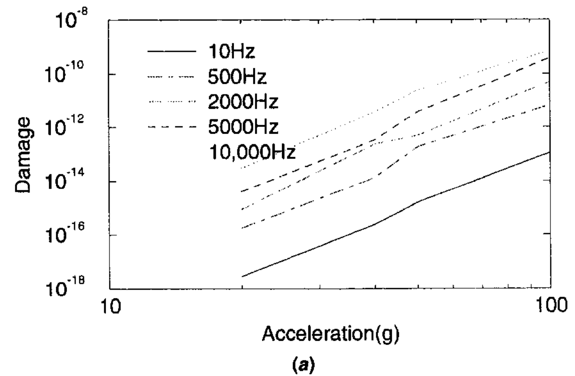


Fig. 10 Damage versus frequency behavior of the solder joint

Figure 10(a) shows the damage experienced in a cycle versus the frequency and the plot is given for different acceleration values. For the acceleration and frequency values given in this figure, the behavior of the solder joint is linear elastic. Hence,



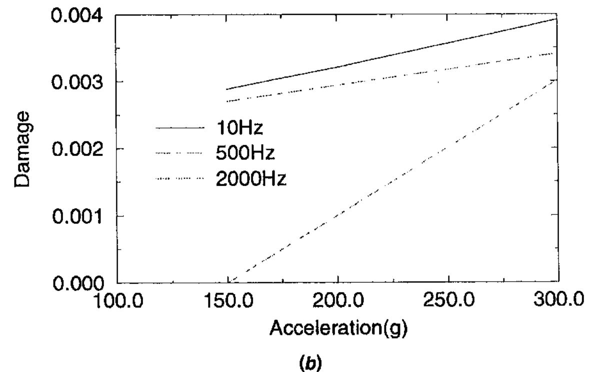


Fig. 11 Damage versus acceleration behavior of the solder joint

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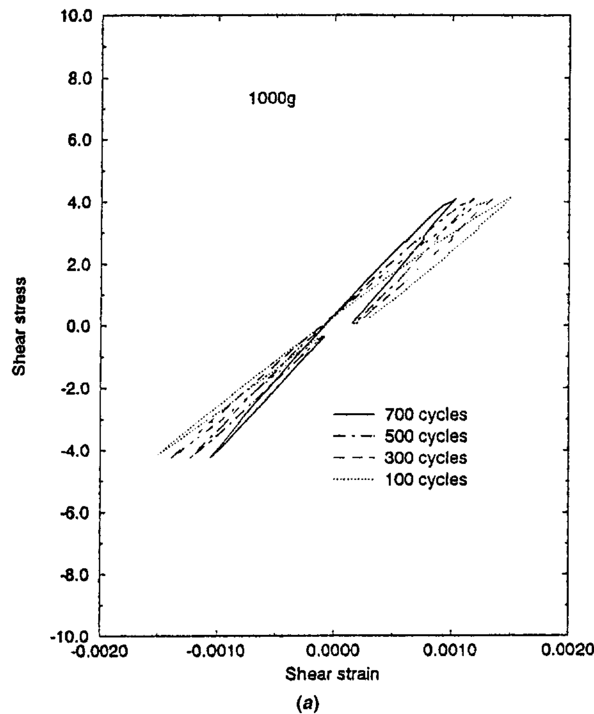
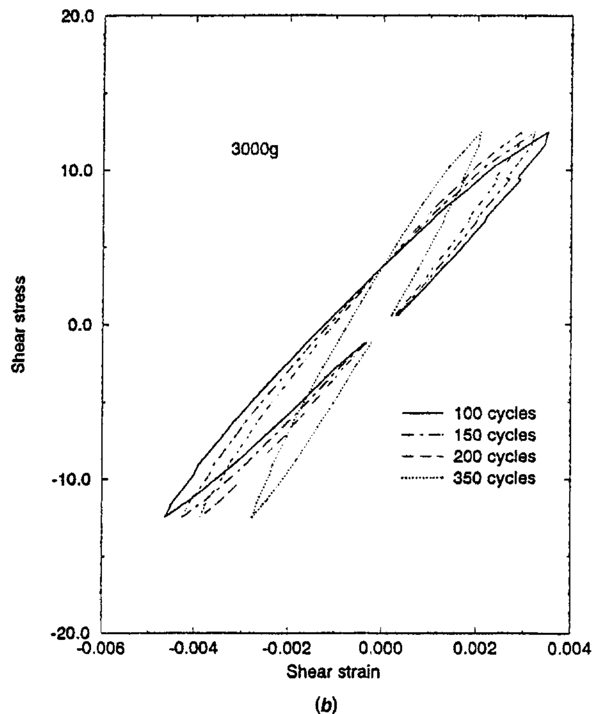


(*a*)



(*b*)

Fig. 12 Shear stress versus shear strain behavior with thermal cycles

the lower frequency loads cause smaller damage per cycle. This is due to the fact that when the acceleration is low enough to cause the solder to remain in the elastic region, the longer periods cannot induce creep and the consequential creep damage. When the solder is in the elastic zone, the large frequency values correspond to very small load periods, such as 10000 Hz for a 0.0001 s period. These loads with very small periods could be considered as shocks. The system experiences larger damage at each cycle as the shock duration is shorter, since the shock becomes more intense. But when the material goes into the viscoplastic range, the creep fatigue dominates the damage value rather than just the shock intensity. This last statement is proven by Fig. 10(*b*), where the damage per cycle is depicted for different acceleration values. For the acceleration values shown, the solder is experiencing viscoplastic deformations. As result, for smaller frequencies, the damage experienced in each cycle is bigger.

Figures 11(*a*) and 11(*b*) show the damage per cycle versus acceleration. The first figure is for the elastic behavior of the solder material. The second figure is for the viscoplastic behavior of the material. When the behavior is elastic (see Fig. 11(*a*)), smaller frequencies lead to lower damage. Yet, for inelastic behavior, smaller frequencies cause larger damage in each cycle and vice versa.

Figures 12(*a*) and 12(*b*) show the shear stress versus shear strain in the solder joint at different normalized temperature cycles. A drop in the ultimate stress level is proportional to the fatigue damage.

In the literature different definitions of failure have been used. For example Solomon's (1986) 50 percent load drop criterion is one of the most popular. But the relationship between this failure definition and fatigue damage is not clear (Guo et al., 1992). In some applications failure is assumed to occur when $D = 1$, even though failure is commonly assumed to occur at a more conservative value, such as 0.7 for electronic equipment or at an even lower one when the loss of life is at stake (Barker et al., 1990; Steinberg, 1988). In this study, no definition of failure is used. Discussion of the percentage of damage that constitutes failure is left out intentionally.

Having not included the thermal loading in this paper was a deliberate decision. Only having dynamic loading makes an interpretation much easier. It has been reported that having in phase or out of phase thermal loading concurrently with dynamic loading makes a significant difference in the overall response of the Pb40/Sn60 solder.

Conclusions

In this paper the dynamic behavior of Pb40/Sn60 has been studied. Low cycle and high cycle fatigue behavior of a solder joint between a leadless ceramic chip carrier and a printed wiring board has been studied. It has been observed that damage experienced due to vibrations can be significant. Contrary to popular belief, the solder alloy does not remain in the elastic range regardless of the frequency of loading and the acceleration level. When the material is in the elastic range, the higher frequency leads to higher damage in each cycle. But when the solder behavior is inelastic, lower frequency vibrations cause higher damage in each cycle than in higher frequency loads.

When the solder joint experiences inelastic deformations during the vibration, ignoring the damage contributions can lead to significant errors in the determination of the low cycle fatigue life. Dynamic load can lead to quick accumulation of fatigue damage. This is due to a high repetition of the vibration cycles in each thermal cycle. The practice of assuming that all vibration induced strains are elastic can lead to serious errors in fatigue life determinations.

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